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Robert H. LaMotte, Ph.D., Principal Investigator, Mandayam A. Srinivasan, Ph.D., and A.M. Annaswamy, Ph.D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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13. ABSTRACT (Maximum 200 words)

The aims and accomplishments of this research were threefold: (1) develop a high precision electromechanical stimulator capable of indenting or stroking stimulus objects across the primate fingerpad under position or force control; (2) investigate how the primate tactual system achieves the sensing of shape and softness of objects and (3) develop a computational theory of haptics suitable for both humans and robots. Using a 4-axis servo controlled tactile stimulator to apply two- and three-dimensional shapes to the monkey fingerpad while electrophysiologically recording responses in slowly- and rapidly- adapting mechanoreceptive nerve fibers (SAs and RAs) it was discovered that spatial parameters of shape were most accurately encoded in the spatially distributed discharge rates of the SA population. In other studies, optimal tactual discriminations of the softness required tactile cues alone for deformable surfaces (rubber) but kinesthetic as well as tactile cues for non-deformable compliant objects. A computational theory using a 3D half-space model of the human and robot finger subjected to arbitrary pressure or displacement loading in any direction gave explicit formulae for coding and decoding. The dynamic interactions occurring between compliant end-effectors and deformable objects were modeled using adaptive control algorithms. The theoretical results can be used to generate testable hypotheses for experiments on human or robot haptics.

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Peripheral Neural Mechanisms of Haptic Touch:

Softness and shape

Final Report for the Office of Naval Research
Grant No. N00014-91-J-1566
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Robert H. LaMotte, Ph.D., Principal Investigator,
Yale University School of Medicine
Tele: 203-737-2720, Fax: 203-737-5220

Mandayam A. Srinivasan, Ph.D.
and A.M. Annaswamy, Ph.D.
Massachussetts Institute of Technology

Three major goals of our previous ONR funded research (1991 - 94) were the following: (1) development of a high precision electromechanical stimulator capable of stroking stimulus objects across the primate fingerpad under position or force control,
(2) investigation of how the primate tactual system achieves the sensing of shape and softness of objects, and (3) development of a computational theory of haptics suitable for both humans and robots.

We summarize below our progress in each of these areas.

1. High precision tactile stimulator

A 4-axis tactile stimulator capable of pressing or stroking stimulus objects under high precision position or force control and a transputer based data collection system capable of recording data at high data rates were developed. The stimulator is composed of a 3-axis positioning system (8 to 12 inches of travel along each axis) actuated by brushless DC linear servomotors together with an additional degree of freedom actuated by a servocontrolled torque motor that carries the test specimens. The position resolution of the system is about a micron or less and the force resolution is of the order of a few mN. A general purpose program was written for the controller that allows the experimenter to choose such parameters as x, y, z and rotary start positions (to select an object in 3D space and an orientation in the horizontal plane), compressional force, mode of contact with the skin (indentation with or without stroking), stroke trajectory (linear or circular), stroke direction, orientation, velocity and acceleration and whether a single trajectory or a series of parallel (or concentric) successively shifted trajectories is used.

Although we are not planning to write a technical paper solely devoted to this subject, it needs to be emphasized that a tremendous effort went into the design and development of this system which was supported in large part by funds from ONR. This system allows us to apply a 3D object to the stationary fingerpad in a natural way and yet provide the kind of stimulus control and reproducibility that is not possible during active touch when the subject controls the mode ofstimulation. For example, we can control and parametrically vary the orientation of the trajectory and, independently, the orientation of the object as well as the compressional force of the objects and the velocity of stroking. Since this not been achieved in any other laboratory, we are hopeful that we will be able to obtain important and novel insights into the neural coding of shape.

2. Sensing of shape in primates

We first measured the capacities of humans to detect deviations from sphericity of ellipsoidal objects applied to the fingerpad and to discriminate differences in the orientation of the major axes of ellipsoids or a cylindrical bar relative to the axis of the finger and/or the direction of stroking the object over the skin (LaMotte et al, 1992). Each object had radius of 5 mm along one axis but differed in radius along the orthogonal axis.

A cylinder, sphere and ellipsoids, had radii ranging from 4.75 to 1 mm. The tactile stimulator (section 1), under computer control, rotated the object to a desired orientation in the horizontal plane and then brought it down onto the stationary fingerpad to achieve a maintained force of 40 gwt. Either the horizontal location was maintained or the object was then stroked along a linear or rotational trajectory over the skin.

Human subjects detected deviations in sphericity on the order of 1mm and, for the cylinder or thinnest ellipsoids, were able to discern differences in orientation of 5-10° and to identify 6 categories of orientation (in 30° steps from 0 to 150°). As is to be expected, discriminations and identifications of orientations deteriorated as the deviation from sphericity reduced. Results were interpreted in relation to the known sensitivity of rapidly and slowly adapting mechanoreceptive nerve fibers (see below) to changes in the magnitude and curvature of the skin brought about by contact with objects of different shapes.

In studies of the tactile neural coding of shape, a series of two- and three-dimensional objects were pressed or stroked across the fingerpads of anesthetized monkeys and evoked responses in cutaneous mechanoreceptive primary afferent nerve fibers were recorded (Srinivasan and LaMotte, 1991; LaMotte and Srinivasan, 1993; LaMotte, Srinivasan, Lu, Klusch-Petersen, 1994). Responses of slowly adapting (SA) and rapidly adapting (RA) fibers were obtained to the application of cylindrical bars, wavy surfaces and ellipsoids. The compressive force was maintained constant during either static indentation, or a stroke; the stroke velocity, object orientation, and stroke trajectory were varied between separate sets of trials.

(a) Cylindrical bars statically indented into the skin
(LaMotte and Srinivasan, 1993).

Cylindrical bars of varying curvature were statically indented into the monkey fingerpad and evoked responses recorded from SA and RA primary afferent fibers. SAs responded to differences in the curvature, both during the ramp and static phases of the indentation. RAs responded only during the ramp phase of the indentation and their responses were not modulated by differences in curvature. The results are consistent with the hypothesis that RAs cannot provide reliable information about the shapes of objects that are merely pressed against or stroked too slowly across the skin.

(b) Wavy surfaces stroked across the monkey fingerpad
(LaMotte and Srinivasan, 1995).

Aperiodic and periodic two dimensional wavy surfaces consisting of smoothly changing patterns of alternating convex and concave cylindrical surfaces of differing curvature were stroked over the skin under constant compressional force and stroke velocity. SA and RA fibers responded with alternating impulse bursts and pauses.

Intensive parameters of the shape pattern such as the magnitude of change in skin curvature, produced due to contact with the object, were encoded in the discharge rates of both fiber types. It was shown that spatial parameters of shapes, such as the width of a convexity and the changes in contour that characterize a shape as belonging to a particular category (e.g. a sphere vs. a cylinder) are encoded in the spatially distributed discharge rates of the SA population. It was shown that the common feature of the spatial discharge rate profile evoked by each convexity, regardless of its radius was the constant slope from the base to the peak and from the peak to the base. Thus, the constant curvature of a cylinder is encoded in the constant slopes of the rising and declining phases of the triangular shaped spatial response profile in the SA population.

(c) Ellipsoids in bas-relief stroked on the skin:
LaMotte, et al, 1994; 1995a; 1995b).

A series of small three dimensional objects of differing shape each mounted on a flat plate were constructed. The objects were ellipsoidally shaped with a radius of 5 mm along one axis, but differing radii of 1, 3 or 5 mm along the orthogonal axis. Each of these 0.5mm high objects was stroked back and forth across the skin under a maintained compressional force (5, 10, or 20 gwt.) along a single linear trajectory or a series of laterally shifted parallel linear trajectories oriented 0,30,60,90,120 or 150° with respect to the long axis of the finger. Three dimensional "spatial event plots" (SEPs) - discharge rate vs location of object on the receptive field - were obtained for SA and RA mechanoreceptive fibers. SEPs of impulses/0.2 mm bin plotted as height over object position (x,y) were interpreted as the spatially distributed responses of a population of fibers at an instance in time. The contour of the base of the SEPs of RAs and SAs encoded the 2-D outline of the object in contact with the skin (quantitative analyses are in progress). The orientation of the outline, determined by a principal component analysis, was closely related to the physical orientation of the object on the skin. An average of five, central, vertical cross-sections through the SEP parallel to the minor axes of the ellipsoids revealed a contour that was related non-isomorphically to object shape. The peak height of this contour (maximum spatial discharge rate) increased and the width of its base (extent of receptor activity in the skin) decreased with increasing object eccentricity for both RAs and SAs. Peak height also changed with changes in contact force, object orientation, and stroke velocity and direction. When peak heights were normalized, object curvature was found to be correlated with the rate of decline of the falling phase in the response profiles for 11 of 16 SAs, but not for the 11 RAs tested. The spatial response measures of shape were more resistant than the intensive measures (discharge rate) to changes in contact force and the direction and velocity of stroking.

Interpreting the SEPs as responses of a spatially distributed population of fibers, the data supported the following conclusions and hypotheses: (1) The contour of the base of the SEPs of RAs and SAs representing the outline of the region of mechanoreceptor activity in the skin encoded the size, shape and orientation of the 2-D outline of the object

in contact with the skin; (2) The third dimension of shape was represented best in the shape of the distribution of spatial discharge gradients (impulses/mm) primarily in the SA fiber population. The shapes of the spatial discharge gradients of RAs were more irregular and variable than those of SAs and exhibited poor or no representations of object shape. It was hypothesized that the distribution of slopes of the spatial discharge rate profile evoked by an object in the SA population encoded the distribution of curvatures on the surface of the object in contact with the skin. The curvature along the minor or major axis of an ellipsoidally shaped object is a constant and was found to be represented by a constant slope along the rising and/or falling phase of a corresponding cross-section through the spatial discharge rate profile. (3) Finally, it was found that the spatial discharge rate codes for the shape, size and orientation of an object were resistant to moderate changes in contact force and the direction and velocity of stroking.

We are currently analyzing the effects of variations in compressional force, stroke velocity, trajectory orientation and object orientation on the spatial discharge rate profiles obtained from the responses of individual SAs and the averaged responses of all SAs tested. These analyses are performed on data collected using the ellipsoids in relief. Those analyses that have been completed support the hypothesis that the relative differences in the shapes of the spatial responses profiles (e.g. differences in slopes of the declining portions of the profiles) obtained in responses to ellipsoids of differing radii are invariant with moderate changes in force, velocity and orientation.

Summary of tactile neural coding of shape in primates:

Major geometrical features of the shapes were well represented in the spatio-temporal responses of SA and RA afferent fiber populations, particularly those of the SAs. Only SAs, and not RAs, provide reliable information about the shapes of objects that are merely pressed against or stroked too slowly across the skin. The results show that the following hypothesis explains qualitatively all the data we have obtained until now: the depth of indentation and the change in curvature of the skin surface are encoded by the discharge rates of SAs; in addition, the velocity and the rate of change in skin surface curvature are encoded by the discharge rates of both SAs and RAs (Srinivasan and LaMotte, 1991). Thus, the intensive parameters of shapes, such as the magnitude of change in skin curvature produced by contact with the object surface were encoded in the discharge rates of SAs and RAs, but this neural code was also influenced by changes in stroke velocity. Spatial parameters of shapes such as the curvature width and the changes in contour that characterize a shape as belonging to a particular category (such as a sphere as opposed to a cylinder) are encoded in the spatially distributed discharge rates of the SA population. It is hypothesized that the distribution of slopes of the spatial discharge rate profile evoked by an object in the SA population encoded the distribution of curvatures on the surface of the object in contact with the skin. This particular measure of the spatial response profile provides a neural code that is probably invariant with moderate changes in the parameters that govern contact conditions between the object

and the skin, such as the contact force or orientation and velocity of its trajectory. Therefore, among the different possible geometric representations of the shape of objects, the intrinsic description, i.e., the surface curvature as a function of the distance along the surface, seems to be relevant for tactile sensing of shape.

Based on a theoretical analysis of the mechanics of contact, we have proposed a mechanism by which shapes of objects within contact regions are perceived through the tactile sense. The curvature of the skin surface under an object, which we know from differential geometry is approximated by the second spatial derivative of surface deflection, is coded without differentiating (which is a noise enhancing process), but by exploiting its relation to surface pressure. Pressure peaks occur where the depths of indentation and/or changes in the skin surface curvature are high. The skin effectively acts as a low-pass filter in transmitting the mechanical signals, and the mechanoreceptors respond to the blurred versions of the surface pressure distribution, thus encoding the shape of the object in terms of its surface curvatures (Srinivasan and LaMotte, 1991).

3. Sensing of Softness in primates (Srinivasan and LaMotte, 1995)

The ability of humans to tactually discriminate the softness of objects was investigated. Novel elastic objects with deformable and rigid surfaces were used. For objects with deformable surfaces, transparent rubber specimens with variable compliances were cast. For objects with rigid surfaces ('spring cells'), telescoping hollow cylinders with the inner cylinder supported by several springs were fabricated. To measure the human discriminability and to isolate the associated information processing mechanisms, psychophysical experiments were performed under three conditions: (1) active touch with the normal finger, where both tactile and kinesthetic information was available to the subject; (2) active touch with local cutaneous anesthesia, so that only kinesthetic information was available; (3) passive touch, where a computer controlled mechanical stimulator brought down the compliant specimens onto the passive fingerpad of the subject, who therefore had only tactile information.

All the human subjects showed excellent softness discriminability in ranking the rubber specimens, and the subjective perception of softness correlated one-to-one with the objectively measured compliance. The ability of subjects to discriminate the compliance of spring cells was consistently poorer compared to that of the rubber specimens. For pairwise discrimination of rubber specimens, kinesthetic information alone was insufficient. However, tactile information alone was sufficient, even when the velocities and forces of specimen application were randomized. For discriminating pairs of spring cells, both tactile and kinesthetic information were found to be necessary. These results can be explained by the mechanics of contact of the fingerpad with the two types of objects, and its effect on tactile information. For objects with deformable surfaces, the spatial pressure distribution, area, and shape of contact regions depend on both the force applied and the specimen compliance, whereas for objects with rigid surfaces, they

depend only on the force applied. Consequently, tactile information is able to code the compliance of the former, but not the latter.

In exploring the mechanics of interaction between either type of compliant object considered here with human or monkey fingerpads in contact with them, we have measured the variation of force over time for various approach velocities. For the rubber specimens, we have measured the time-variations of contact areas as well, and computed the corresponding variations of average pressure. We have performed statistical correlation studies to test if the subjects' psychophysical performance was based on cues such as ramp time, force rate, area rate or pressure rate. Electrophysiological recordings from single slowly and rapidly adapting mechanoreceptive afferent fibers innervating the monkey fingerpads enabled us to examine the nature of the peripheral neural code in the human discrimination of softness. The results show that none of the purely temporal measures, such as the ramp time, force rate, area rate, pressure rate, or neural impulse rate account for the discriminability of softness by the subjects. This empirical result, together with a theoretical analysis of the mechanics of contact, lead us to the hypothesis that the subjects' fine discriminability of the softness of rubber specimens is based on spatio-temporal neural codes stemming from the spatio-temporal variation of pressure distributions within the regions of contact. Further support for this hypothesis has come from our recently obtained images of these contact regions using videomicroscopy.

4. Development of a Computational Theory of Haptics

Our research on computational theory of haptics is focused on developing a theoretical framework for studying the information processing and control strategies common to both humans and robots performing haptic tasks. For example, although the "hardware" of the tactile apparatus in humans and robots are different, they have the common feature of mechanosensors embedded in a deformable medium. Therefore the mechanistic analyses needed to solve the computational problem of coding (predicting sensor response for a given mechanical stimulus at the surface) and decoding (inferring the mechanical stimulus at the surface by suitably processing the sensor response) are similar for human and robot tactile sensing systems.

We first developed such a "computational theory" using a simplified 2D half-space model of the human or robot finger subjected to arbitrary pressure or displacement loading conditions normal to the surface, and gave explicit formulae for the coding and decoding problems (Srinivasan, 1988). We have now expanded these results to a more general 3D half-space model where the load direction can be completely arbitrary (Karason et al., 1994). Explicit solutions for the coding problem are given and enable the selection of a useful set of relevant stimuli as well as the choice of sensors appropriate for maximizing the information about the stimulus on the skin surface. The solution of the decoding problem is also given, both for the idealized noise-free case and for the realistic case with measurement noise. For the latter, the solutions are shown to be numerically stable and

optimal.

In our work during the previous years, we were successful in answering basic identification and control issues that arise during manipulation of compliant objects using compliant fingerpads (Annaswamy and Srinivasan, 1993; 1994; 1995). In order to understand the fundamental aspects of these tasks, we have analyzed the problem of identification of compliant objects with a single finger contact, as well as under a two-finger grasp. Using lumped parameter models, we have carried out the identification of human and object parameters, using either force or displacement inputs to the rigid backing of the end-effector. Based on identified parameters, control strategies are developed to achieve a desired manipulation of the object in the workspace.

We have also modelled the dynamic interactions that occur between compliant end-effectors and deformable objects by a class of nonlinear systems. It was shown that standard geometric techniques for exact feedback linearization techniques were inadequate. New algorithms were developed by using adaptive feedback techniques which judiciously employed the stability characteristics of the underlying nonlinear dynamics. In both theoretical and simulation studies, it was shown that these adaptive control algorithms led to successful manipulation. The theoretical results can be used to generate testable hypotheses for experiments on human or robot haptics.

3.5 Publications and Manuscripts

Major publications:

Shape:

1. Srinivasan, M.A. and LaMotte, R.H. Encoding of shape in the responses of cutaneous mechanoreceptors. In: Information processing in the somatosensory system, edited by O. Franzen and J. Westman. MacMillan Press, London, 1991.

2. LaMotte, R.H. and Srinivasan, M.A. Responses of cutaneous mechanoreceptors to the shape of objects applied to the primate fingerpad. Acta Psychologica. Vol. 84, pp. 41-51, 1993.

3. LaMotte, R.H., Srinivasan, M.A., Lu, C. and Klusch-Petersen, A. Cutaneous neural codes for shape. Can. J. Physiol. Pharmacol. Vol. 72, pp. 498-505, 1994.

4. LaMotte, R. H. and Srinivasan, M. A. Neural coding of shape: Responses of cutaneous mechanoreceptors to wavy surfaces stroked across the monkey fingerpad, 1995 (to be submitted to J. Neuroscience).

5. LaMotte, R.H., Lu, C. and Srinivasan, M.A. Tactile neural codes for the shapes and orientations of objects. In: Somesthesis and the neurobiology of the somatosensory cortex, edited by O. Franzen, R. Johansson and L. Terenius. Birkhauser Verlag AB, Basal, 1995a (in press).

Softness:

6. Srinivasan, M.A. and LaMotte, R.H. Tactual discrimination of Softness, J. Neurophysiol. Vol.73, No. 1, pp.88-101, 1995.

Computational Theory:

7. Annaswamy, A.M. and Seto, D. Object Manipulation using Compliant Fingerpads: Modeling and Control. ASME Journal of Dynamic Systems, Measurement, and Control. Vol. 115, pp. 638-648, 1993.

8. Seto, D., Annaswamy, A.M. and Baillieul, J., Adaptive Control of a Class of Nonlinear Systems with a Triangular Structure. IEEE Transactions on Automatic Control, Vol. 39, pp. 1411-1428, 1994.

9. Karason, S. and Annaswamy, A.M. Adaptive control in the presence of input constraints. IEEE Transactions on Automatic Control, Vol. 39, No. 11, pp. 2325-2329, 1994.

10. Annaswamy, A.M. and Karason, S. Discrete-time adaptive control in the presence of input constraints. Automatica (in press).

11. Annaswamy, A.M. and Srinivasan, M.A. The Role of Compliant Fingerpads in Grasping and Manipulation: Identification and Control, Chapter in a book to be published by the Institute of Mathematics, Springer Verlag, (in press).

Rehabilitation:

12. Greenspan, J. and LaMotte, R. H. Cutaneous mechanoreceptors of the hand: Experimental studies and their implications for clinical testing of tactile sensation. J. Hand Terapy 6:75-82, 1993.

Human-machine interfaces:

13. Bishop G, et al., Research Directions in Virtual Environments: Report of an NSF Invitational Workshop, Computer Graphics, Vol. 26, No. 3, pp. 153-177, 1992.
(Dr. Srinivasan wrote the sections on Haptic Perception and Haptic Interfaces)

14. Srinivasan MA, Sections on Haptics (some co-authored with Salisbury JK), In Virtual Environment Technology for Training, BBN Report No. 7661, Prepared by The Virtual Environment and Teleoperator Research Consortium (VETREC) affiliated with MIT, 1992.

Refereed Conference Publications:

Computational Theory:

1. Annaswamy, A.M. and Srinivasan, M.A. (1990) Manipulation of compliant objects with compliant fingerpads: Identification and control issues, Proceedings of the IEEE Conference on Decision and Control, Honolulu, Hawaii.

2. Annaswamy, A.M. and Srinivasan, M.A. (1991) Adaptive control for grasping and manipulation of compliant objects with compliant fingerpads, Proceedings of the American Control Conference, Boston.

3. Annaswamy AM and Seto D, Manipulation of compliant objects using tactile robots in the presence of nonlinear dynamics, Proceedings of the 1991 CDC, Brighton, England, December 1991.

4. Annaswamy AM, Seto D, and Baillieul J, Adaptive Control of a Class of Nonlinear Systems, Proceedings of the Seventh Yale Workshop on Adaptive and Learning Systems, New Haven, Ct., May 1992.

5. Annaswamy, A.M. and Seto, D. Object Manipulation using Compliant Fingerpads: Modeling and Control. ASME Winter Annual Meeting. November 1992.

6. Seto, D., Annaswamy, A.M. and Baillieul, J. Adaptive Control of a Class of Nonlinear Systems with a Triangular Structure.
Proceedings of the Conference on Decision and Control, Tucson, AZ, December 1992.

7. Karason, S. and Annaswamy, A.M. Adaptive control in the presence of input constraints. Proceedings of the 1993 American Control Conference, San Francisco, CA, June 1993.

8. Annaswamy, A.M. and Karason, S. Discrete-time adaptive control in the presence of input constraints. Tech. Report 9302, Adaptive Control Laboratory, Dep. Mechanical Eng., MIT, Cambridge, MA 02139.

9. Annaswamy, A. M. and Srinivasan, M.A. A Study of Dynamic Interactions between Haptic Interfaces and Compliant Fingerpads, Proceedings of the Motion Control Workshop, Berkeley, CA, March 1994.

10. Karason, S. P., Srinivasan M. A. and Annaswamy A. M., Tactile Sensing of Shape, Proceedings of the workshop organized by the Center for Information Driven Mechanical Systems (CIDMS), Dept. of Mechanical Engineering, MIT, September, 1994.

Conference Abstracts:

1. Srinivasan, M.A. (1991) Tactual interfaces: The human perceiver, In: Human - Machine Interfaces for Teleoperators and Virtual Environments, Eds. Durlach NI, Sheridan TB and Ellis SR, NASA Conference Publication 10071.

2. Srinivasan, M.A. and LaMotte, R.H. (1991) Tactile discrimination and representations of texture, shape, and softness, In: Human - Machine Interfaces for Teleoperators and Virtual Environments, Eds. Durlach NI, Sheridan TB and Ellis SR, NASA Conference Publication 10071.

3. Srinivasan MA, Computations in tactile sensing, Proceedings of Computation and Neural Systems (CNS*92) meeting, San Francisco, July 1992.

4. LaMotte RH, Srinivasan MA and Klusch-Petersen A, Tactile discrimination and identification of the shapes and orientations of ellipsoidal objects, Society for Neuroscience Abstracts, 18:830, 1992.

5. LaMotte, R.H., Srinivasan, M.A., Lu, C and Petersen, A. K. Responses of cutaneous mechanoreceptors to two- and three-dimensional shapes stroked across the monkey fingerpad. Neurosci. Soc. Abstr. Vol. 19, p. 105, 1993.

6. LaMotte, R.H., Lu, C. and Srinivasan, M.A. Peripheral neural representation of the shapes and orientations of three-dimensional objects stroked across the monkey fingerpad. Soc. Neurosci. Abstr. 1995b (in press).

Training Data

(1991-92)
Graduate Students = 2 (1 US citizen and 1 Foreign)
Undergraduate Students = 2 (both Foreign)
Additional Personnel: 1 Scientific Programmer (US permanent resident) and 2 Research Assistants (1 US citizen and 1 Foreign)

(1992-93)
Steingrimur Karason completed his Master's thesis at MIT in May 1993. (Research Assistantship funded by Professor Annaswamy's
NSF PYI award, and not supported by ONR).

(1993-94)
TRANSITION OF IDEAS TO MILITARY LABORATORY AND APPLICATION

The results of our basic scientific research on the human haptic system, which were obtained with major funding from ONR over the past several years, have contributed significantly to the initiation of a new research program on the development of haptic interfaces for naval training with virtual environments (VE) at MIT. This is one of six projects to develop a multimodal VE testbed for naval training, awarded to the Virtual Environment and Teleoperation Research Consortium (VETREC) by the Naval Air Warfare Center, Training Systems Division (NAWC/TSD). VETREC includes research groups from MIT, Brandeis and BBN Laboratories, Inc. Dr. David Fowlkes is the contact person at NAWC/TSD.

TRAINING DATA
Mr. Steingrimur Karason (non-US citizen) is developing a computational theory of haptics as a part of his PhD thesis (Research Assistantship partly funded by Professor Annaswamy's NSF PYI award, and by a URI grant from ONR).